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Hazard Map of Rincón de la Vieja Volcano, Costa Rica: Qualitative Integration of Computer Simulations and Geological Data

Mapa de Riscos do Vulcão Rincón de la Vieja, Costa Rica: Integração Qualitativa de Simulações Computacionais e Dados Geológicos

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Resumo

Um mapa de risco do vulcão Rincón de la Vieja foi elabordo tendo como base a integração e análise de informações existentes, modelos computacionais e dados de campo. +-9-Até 2018, esse vulcão não possuia um mapa oficial de risco que permitisse a aplicação do gerenciamento de desastres vulcânicos ao planejamento territorial. Espera-se que, eventualmente, os resultados deste trabalho sirvam como uma ferramenta para as instituições de tomada de decisão, a fim de aplicar melhores práticas para o planejamento do uso da terra e executar o gerenciamento de risco, considerando o componente de perigo vulcânico. O documento foi elaborado com base em três principais fontes de dados: 1. Dados coletados em campo, 2. Modelos determinísticos e; 3. Trabalhos anteriores. O resultado obtido foi um mapa de tipo qualitativo integrado (Calder *et al.*, 2015), que mostra as principais ameaças que a curto e médio prazo podem afetar a área de estudo como resultado da atividade eruptiva de Rincón de la Vieja.

Palavras-chave: Gestão de riscos; lahars; fluxos piroclásticos

Abstract

A volcanic hazards map was prepared for Rincón de la Vieja volcano, based on the integration and analysis of existing information, computational models and fieldwork data. Until 2018, this volcano did not have an official volcanic hazard map, necessitating the application of volcanic disaster risk management to territorial planning of the region. Results of this work will serve as a tool for the decision-making institutions, providing guidance to apply better practices for land use, planning and perform risk management, considering the volcanic hazard component. The document was prepared based on three main data sources: 1. Data collected in the field, 2. Deterministic models and; 3. Previously published data. The result obtained is an integrated qualitative map (Calder *et al.*, 2015), which shows the main volcanic threats in the short and medium term, which can affect the study area as a result of the eruptive activity of Rincón de la Vieja.

Keywords: risk management; lahars; pyroclastic flows

1 Introduction

Various researchers since the first decades of the 20th century has been studying eruptive activity and hazards of Rincón de la Vieja. Initially, documents by Tristán-Fernández (1921) suggest that there might have been a slight morphological change in the active crater between the 19th and 20th centuries. Healy (1969) described the morphology of the summit using aerial photographs and his own field work; he was the first to mention that the structure is made up of at least nine cones distributed along two alignments.

Benner (1987) made a geological mapping that allowed to characterize the eruptive history, categorize the basic petrography of the units that form the volcanic building. This author also, based on the stratigraphic record, the topography and the climatic characteristics, assessed the potential threats for future eruptions, considering lahars, lava flows and tephra fall. This study excluded the assessment of long-term threats.

Boudon *et al.* (1996), characterized the proximal pyroclastic deposits of the eruptions of 1966-1970 and 1991-92, and made a distribution map for these materials. They also pointed out that the explosiveness of these events is the product of the interaction between a shallow magmatic body, the crater lake and the active hydrothermal system of the volcano. In addition, they stated that the main threat during subsequent eruptions could correspond to lahars, which would affect the valleys located on the northern flank of the volcano.

Most historical eruptions of this volcano have been classified as phreatic (Barquero & Segura, 1983; Barquero & Fernández, 1987; GVP, 1991a; b; c). However, the deposits of 1966-70 and 1991-98 eruptions contain scoria and breadcrust bombs, materials that are indisputably associated with juvenile eruptive products Alvarado (1989; 2011).Fernández *et al.* (1991) described the eruptive activity presented on May 6, 7 and 8, 1991. Elaborated an ash fall map and made a mapping of some of the areas affected by lahars and its deposits, indicating that the flows were produced by the overflow of the crater lake and that the most important volcanic threat for the north-northwest flank comes from the lahars.

Kempter *et al.* (1996), studied the geology of the southwestern flank of the volcano and determined, through studies of grain size of the Río Blanco tephra deposit (~ 3770 ± 130 years BC), that the eruption in which these materials were deposited it was subplinian, with an eruptive column that reached approximately 16 km in height. In addition, they conducted a qualitative risk assessment, concluding that future eruptions of this volcano would be prone to maintain the explosive style, extending the area of whorst danger several kilometers north of the active crater.

Paniagua *et al.* (1996), made a synthesis of the volcanic threat considering the geological and stratigraphic framework, petrography, geochemistry, thermal manifestations, structures, climate and recent eruptive activity. Subsequently, they made a series of recommendations on the actions to be taken before and during a volcanic eruption. In addition, these authors collected information on the eruptions presented during the eighteenth, nineteenth and twentieth centuries, including the occurrence of phreatomagmatic eruptions, emission of gases, lahars, ash fall, pyroclastics and acid rain.

Regarding the occurrence of lahars in the Rincón de la Vieja volcano, there is a record of some flows that descended through the Pénjamo and Azul rivers during 1991 and 1995 (Soto, 2004; Soto *et al.*, 2003b). However, there is no record of fatalities. Alvarado (1993) mentions that on May 8, 1991, a lahar occurred that traveled a distance of 16.6 km on the northern flank of the volcano.

Soto *et al.* (2003a) conducted a study of the most important eruptions since 3800 BP., and determined that during that period, at least one subplinian eruptive event occurred (~ 3770 ± 130 years BP) and that an eruption generated significant pyroclastic flows (~ 1520 BP) to the west of the eruptive focus, as well as Kempter (1997) had already suggested it.

Paniagua *et al.* (1996) conducted an analysis of the damage caused by the eruptive activity of Rincón de la Vieja during 1995. Subsequently, Aguilar & Alvarado (2014) carried out a study on the economic losses associated with volcanic eruptions in Costa Rica between 1953 and 2005. They determined that the eruptions presented by the Rincón de la Vieja, during the decades of the sixties and nineties of the twentieth century, caused losses to the agricultural and livestock sector, as well as damage to the road infrastructure (bridges), particularly as a result of the fall of ash, acid rain and lahars.

2 Local Setting

Rincón de la Vieja volcano is located 25 km NNE from the Liberia town, Guanacaste. It is a complex stratovolcano and the only one with historical eruptive activity in the Guanacaste volcanic mountain range (Bullard, 1956; Aguilar & Alvarado, 2014). Its maximum elevation is 1916 m a.s.l., and at least nine eruptive vents are recognizable on its summit (Healy, 1969). The active crater harbors a hot and hyper acidic lake (Alpízar *et al.*, 2014), in which phreatic eruptions occur relatively frequently (Figure. 1).

The eruptive activity of Rincón de la Vieja volcano during the last 3800 years is relatively well documented. Several authors have carried out the tasks, both to document the eruptive activity, and to map, describe and date the recognizable deposits.

From the analysis of the collected information, it becomes evident that, during the last 4000 years, the volcano has had at least three periods of eruptive activity well marked:

1. A subplinian eruption, described by Kempter *et al.* (1996), Kempter (1997), Soto *et al.* (2003a), Soto (2004) and characterized by deposits of dacitic pumice. The deposits of this eruption extend up to about 30 km away from the WNW of the active crater (Soto, 2004).

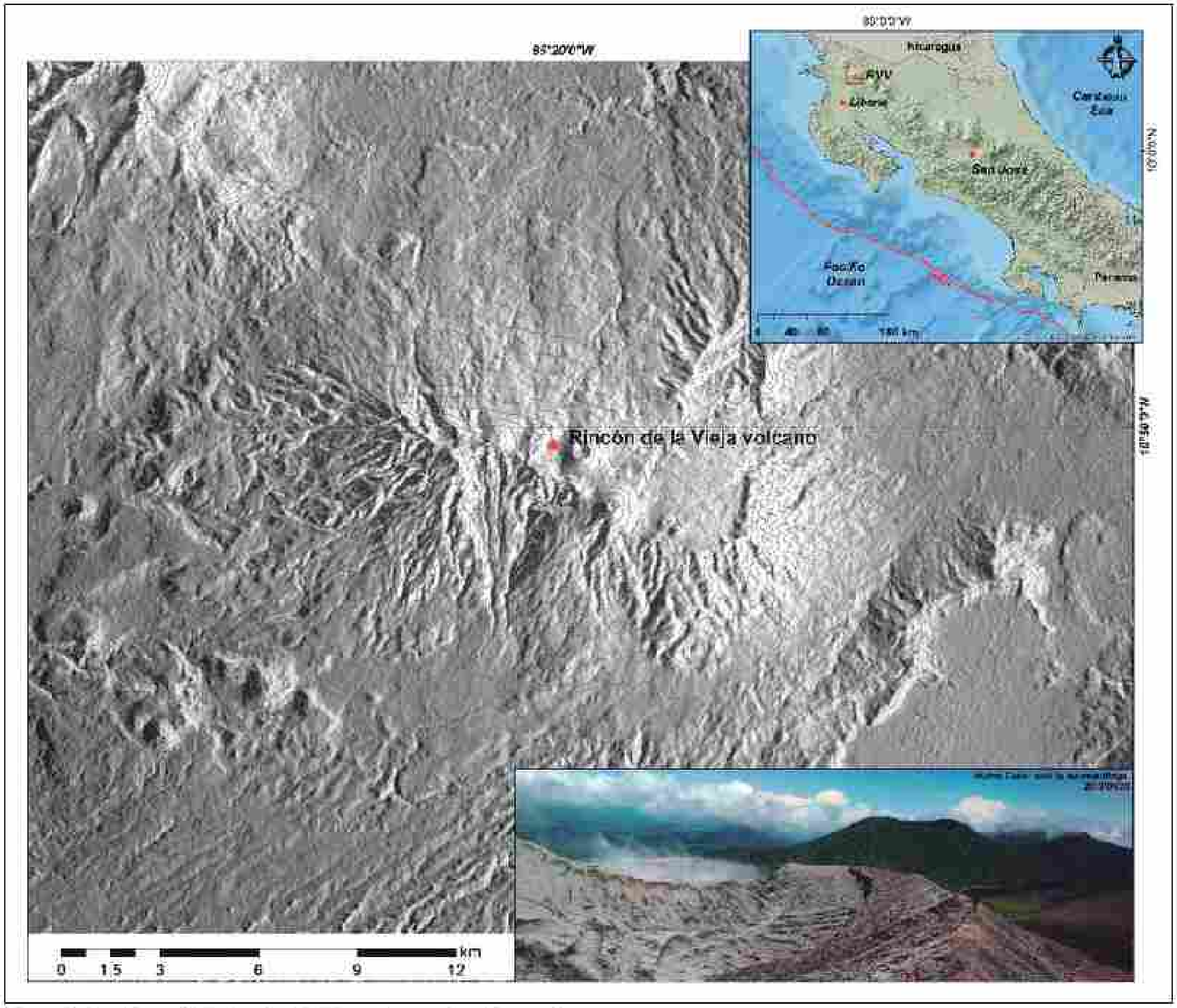

Figure 1 Location of Rincón de la Vieja volcano and active crater area.

2. An eruption with generation of pyroclastic flows of slag channeled towards the northern flank of the volcano. These flows reached, according to Soto *et al.* (2003a), about 10 km away from the eruptive focus.

3. The historical eruptive period, which includes the activity occurred and documented from the XIX century to the present. The activity during this period has been characterized by phreatomagmatic eruptions. The most important was the vulcanian explosion occurred on January 17, 1967 (Soto *et al.*, 2003a). Phreatomagmatic eruptions occur separated by intervals of four to five decades of relative calm, during which phreatic activity predominates.

It should be noted that, for the lapses elapsed between the three periods mentioned, although the corresponding eruptive deposits have not yet been described, there is a geological record on the summit of the volcano, consisting mainly of layers of tephra, which shows periods of phreatomagmatic eruptive activity, so its subsequent analysis should not be ruled out.

3 Methodology

The investigation began with an exhaustive process of bibliographic recopilation, about two fundamental issues: a) the previous eruptions the Rincón de la Vieja volcano; b) existing volcanic hazard maps for this volcano.

The fieldwork consisted in mapping and validation of the bibliographic information collected; we consulted primary and secondary sources of information, such as thesis, existing hazards maps, historical documents, journals and internal reports of the volcano observatories, among others.

Mapping of lahars and other volcanic products was done. Based on the information collected on known eruptive activity (historical and prehistoric), the main hazards associated with the Rincón de la Vieja volcano were identified and the volcanic hazard map was generated.

The modeling of the lahars used as a basis for the description of the affectation scenario was made using a Laharz computer tool (Schilling, 1998). The results of the model were validated with field information in terms of the scope of the deposits.

First, a general model was drawn up covering all the slopes of the volcano; this considers variable volumes (8×10^5 m^3, 1×10^6 m^3, $1{,}5 \times 10^6$ m^3, 2×10^6 m^3 y $2{,}5 \times 10^6$ m^3) and a digital elevation model (DEM) with spatial resolution of 12.5 m from the ALOS PALSAR sensor (Alaska Satellite Facility, 2015). The starting points were located in the upper parts of the rivers and streams that are born on the slopes of the volcano.

The choice of modeled volumes was based on the following criteria:

1. Reach that the lahars generated towards the north of the Rincon de la Vieja volcano have been in the past (Alpizar, 2018).

2. Frequency with which small volume lahars occur in the study area;

3. Documented previous experiences, for which the volumes or the approximate distance reached by the flows are known (Irazú and Arenal volcanoes (Alvarado, 1993));

4. Previous validations, performed to models based on the old lahar deposits at Irazu and Rincon de la Vieja.

For delimitation of the threat zone by pyroclastic flows, the tool for the calculation of proximal threat zones of Laharz was used (Schilling, 1998). This tool is based on the energy line model proposed by Heim (1932), which with some modifications, still is widely used. The Heim's coefficient or friction's coefficient, relates the elevation of the flow's starting point "H", which strongly controls the flow potential , with the distance "L" reached by this (Malin & Sheridan, 1982). The distal part of the flow corresponds to the intersection between the energy line and the topographic surface. In this case, L corresponds to the maximum distance reached by pyroclastic flows of blocks and ashes in the past (Figure 2).

Due to the strong influence of the topographic gradient on the gravitational flows, the pyro-

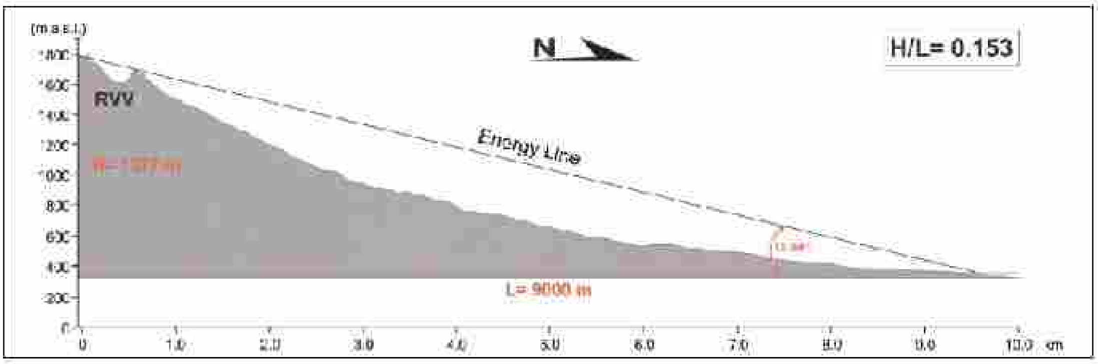

Figure 2 Energy line for block and ash pyroclastic flows

clastic current will not reach its maximum extension in all directions, but the flow will go preferentially towards those areas with steeper slopes (Malin & Sheridan, 1982).

To model the ash fall, we used the Ash3D tool, developed by the USGS. It runs online, and as part of its input data, takes a wind file provided by the numerical weather prediction model of the NOAA Global Forecasting System (Mastin *et al.*, 2013). The modeled scenarios were defined as A (vulcanian eruption) and B (sub plinian eruption) and their characteristics are:

Scenario A: Proposed by Soto *et al.* (2003), an eruptive column height of up to 7 km above the crater and a volume of up to 10^6 m^3. The duration of this eruption is nine hours, as Kempter (1997) calculated.

Scenario B: The one described by Kempter (1997), with a height for the eruptive column of up to 16 km above the crater, a volume of 0.25 km^3 and a duration of at least nine hours.

To delimit the area affected by gases and acid rain, satellite images of the Google Earth ® platform dated 26/03/2015 been used. The areas of "dead zone" around the active crater are considered part of the influence area, in which the vegetation is scarce or nonexistent, and where during fieldwork, the persistence of the volcanic gases in high concentrations was confirmed.

4 Analysis of Volcanic Hazard

It has been determined that the main volcanic hazards of the northern sector of Rincón de la Vieja in short term, are pyroclastic flows, lahars, ash fall, affectation by gases and acid rain. Lava flows and falling blocks / bombs would be restricted a few kilometers away from the source, and are unlikely to reach the nearest populations, considering that the closest homes are 5 km away from the active crater.

4.1 Pyroclastic Flows

The deposits of the only pyroclastic flow identified for this volcano, are moderately welded, have poor selection, containing from ash, up to blocks that are metric, sub angular to sub rounded and with low sphericity. The deposit is supported by an ash matrix and structures characteristic of pyroclastic flows were observed, such as puzzle structures and degassing chimneys (Figure 3). Its origin is associated with the pyroclastic flow described by Soto *et al.* (2003b).

In terms of the numerical model, for a coefficient of Heim equal to 0.15, a distribution of pyroclastic flows channeled towards the northern sector of the volcano was obtained (Figure 3). The elevation of the active crater was considered as the starting point of the flows, and as the distance L, the maximum distance traveled by the flows in the past. The distribution of the flows towards the north is associated with the fact that the active crater is located at a lower topographic elevation than other important structures of the massif, which causes that there are topographical barriers that would eventually prevent the progress of the flows towards the southern flank.

4.2 Lahars

Due to factors such the presence of an intracrateric lake and the prevailing climatic conditions at

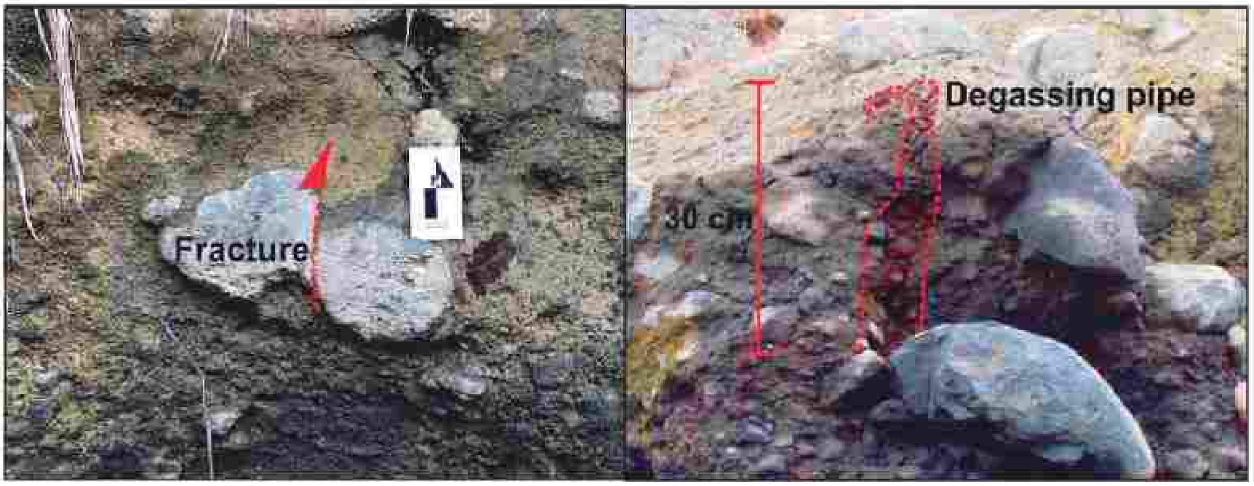

Figure 3 Typical structures of block and ash flow. Left: Jigsaw structure; right: Degassing pipe. Outcrop located 6.5 km away from the summit, Pénjamo riverside.

the upper and middle parts of the volcano's northern flank, lahars are one of the most common events associated with its activity, having been described in detail by Paniagua *et al*. (1986), Kempter (1996), Kempter & Rowe (2000), Soto *et al*. (2003b) and Alpízar (2018). All these authors have agreed that the area most likely to be affected by lahars is located in the northern sector of the volcano. However, facing an eruptive scenario with VEI ≥ 3, the occurrence of lahars in the other flanks should not be ruled out.

The lahars that have affected the northern flank of the volcano, have been channeled generally by the Azufrada stream and the Pénjamo and Azul rivers, traveling up to 16.6 km from the crater (Alvarado, 1993) and affecting the Cucaracho river bed. Authors such as Kempter (1996), Kempter & Rowe (2000) and Soto *et al*. (2004), have described in detail the deposits and suggest that the Pizote River could become affected by these flows in the event of a large-scale eruption, or as a result of an eventual collapse of the northern flank of the active crater.

4.2.1 Characteristics of Deposits

During the fieldwork, both old and recent lahar deposits and pyroclastic flows were analyzed. Here we describe the characteristic deposits of flows that have descended through the channels of the Azul and Pénjamo rivers.

In the lower parts of the northern flank of the volcano, 7 km far from the active crater, it is possible to identify at least three levels of terraces, as well as blocks that exceed 3 m in diameter and trunks up to 8 m in length, of which it has been observed that they are preferentially oriented parallel to the river channel, so it is possible to affirm that they have been deposited by lahars (Figure 5).

Overlying the pyroclastic flow described previously (Figure 6), several deposits of lahars were observed, characterized by the presence of clay in its matrix, poor selection, inverse gradation and the presence of organic matter and bubbles in the matrix. In addition, the absence of deposition structures such as laminations indicates that these are not normal stream flows. In this site the deposits of at least two recent lahares were identified and when compared with the descriptions of Soto *et al*. (2003), it is interpreted that the lower unit corresponds to the hot lahars of 1991, while the upper unit is more recent.

4.2.2 Deterministic Models

Lahars are the events with most possibility of occurrence in the study area since their reached distance, mortality and destruction usually have significant magnitude (Alpízar, 2018), and deterministic models of lahar affectation have been developed for Rincón volcano de la Vieja using the Laharz tool (Schilling, 1998).

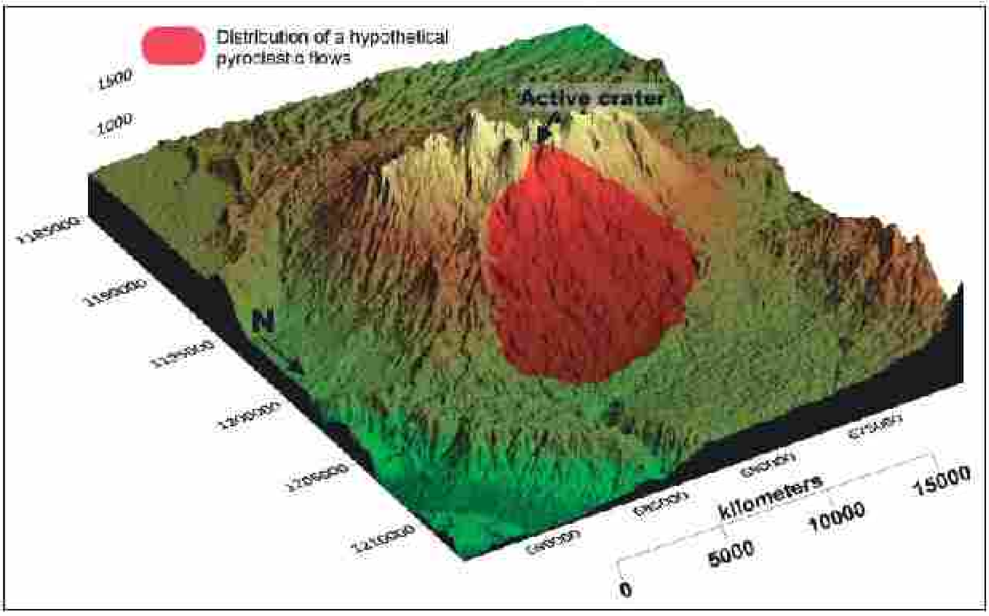

Figure 4 Hypothetical area that could be affected by pyroclastic flows. Results of model with an H/L = 0.15.

Figure 5 Blocks and trunks deposited by recent lahars and mentioned levels of terraces. Place located near to Pénjamo river bridge, 7 km away from the summit.

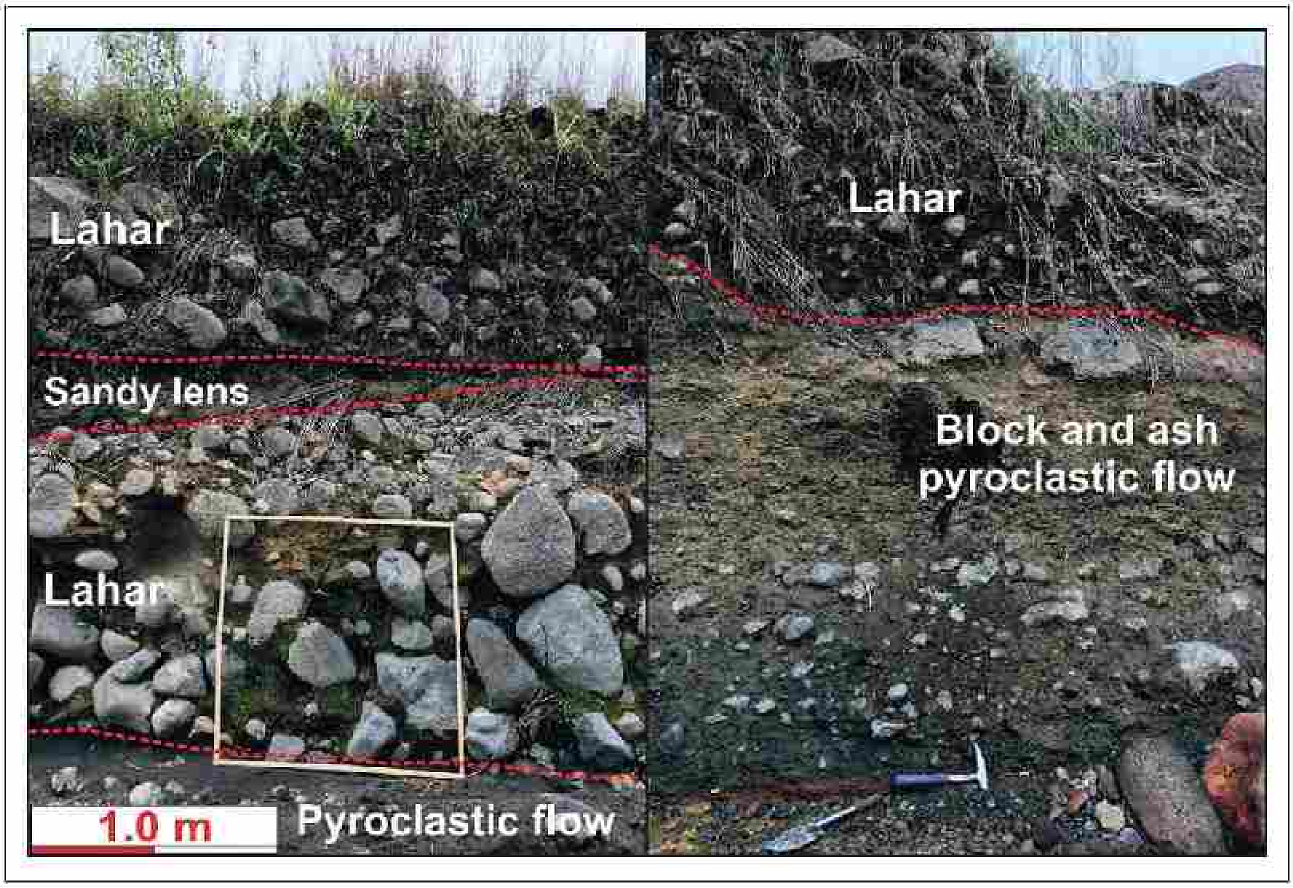

Figure 6 Outcrop located 7 km away from the active crater, where the lahars overlie the pyroclastic flow deposits.

To emphasize the impact that the northern sector would have due to lahars that descend through the Blanco, Azul and Pénjamo rivers, in Figure 7 the results of the model are displayed for variable volumes between 8 x 10^5 m^3 and 2,5 x 10^6 m^3.

It is important to consider that the limits established in the models are not definitive and may vary according to the conditions of each flow. In this case, because the pixel size of the MED used for the modeling is 12.5 m, this value can be considered as the uncertainty of the models obtained. Thus, for the modeled volumes, it is possible that the flood zones vary up to 12.5 m on both sides of the contour.

4.3 Ashfall

Authors such as Kempter *et al*. (1996), Kempter (1997), and Soto *et al*. (2003a), made maps of ash fall based on the geological record and their results coincide in that the emitted ash presents a dispersion axis oriented towards the west of the active vent. In several outcrops located at the western flank of the volcanic building, have been found deposits of ash and pumice of metric thickness, those of any, according to Soto *et al*., (2003), corresponding to the subplinian eruption of 1766 BC ± 130.

During 1966 eruptions, about 40 cm of ash fell on the top of the volcano, and for the activity of 1995, the fall of material was reported up to 30 km west of the active crater.

However, although during most of the year the winds come from the east, it is possible that the direction changes during certain periods. It is for this reason that the proposed volcanic hazard map, in addition to considering the delimited area based on the geological record, contemplates two eruptive scenarios modeled at three different times of the year.

4.3.1 Modeling of Ash Affectation Scenarios

For scenarios A1, A2 and A3, corresponding to the months of January, May and October respec-

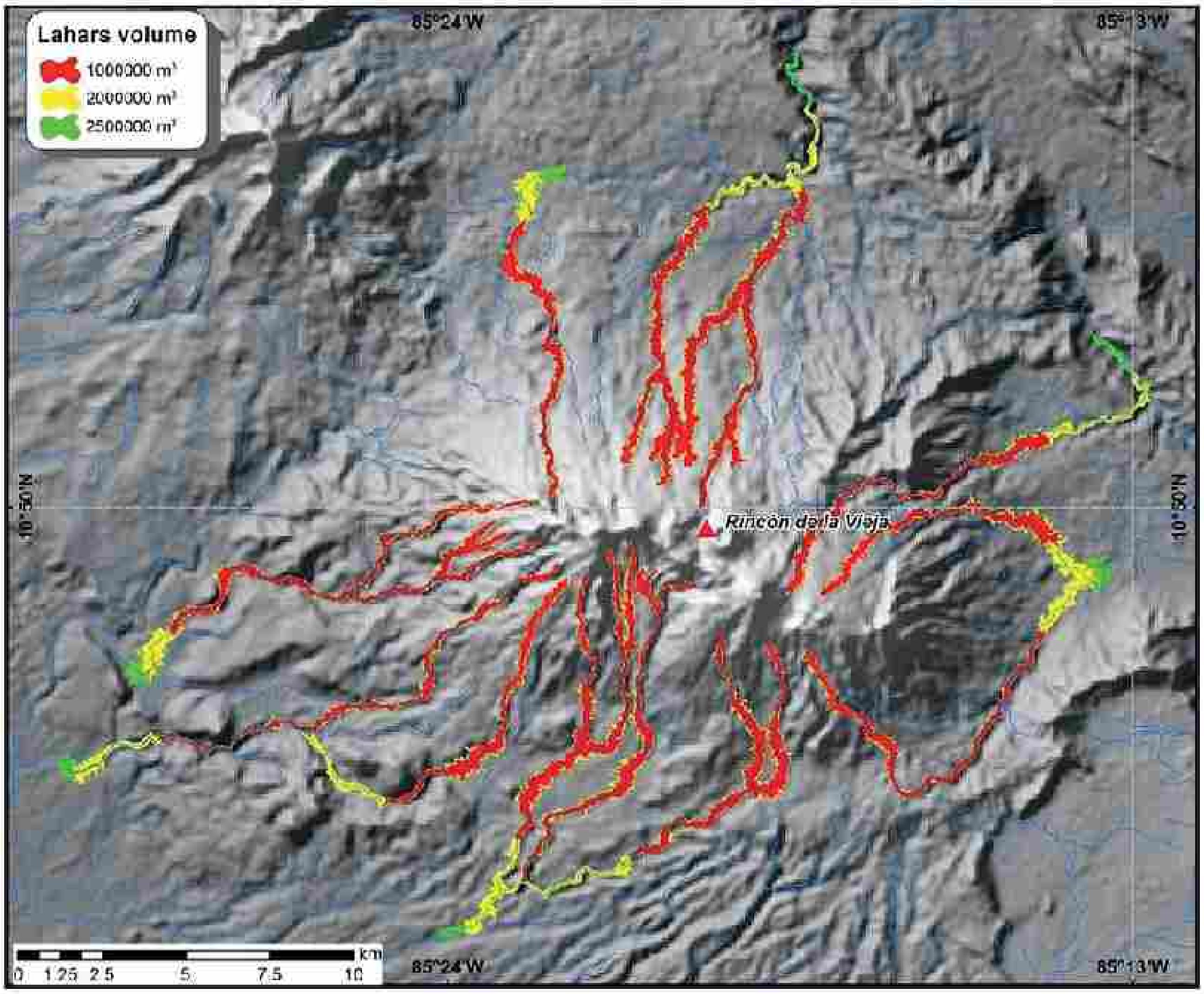

Figura 7 Lahar inundation model

tively, maximum thickness of 30 mm was obtained. According to the model, the distribution axis of the deposit would be to the southwest in January and to the west in October, reaching a distance of up to 65 km from the crater. For the case of an eruption that occurred in May with the characteristics described for scenario A, the distribution of the ash would be towards the east and southeast of the eruptive focus, with maximum thickness of 30 mm and the deposit would reach a maximum distance of 28 km from the emission center (Figure 8).

Regarding B scenarios (Figure 8), in the same eruptive conditions, during the three seasons of the year, the ash cloud behavior is extremely variable, so that, if the eruption occurred in January, as scenario B1 states, the axis of distribution of the deposits would have NE-SW direction, distributing to both sides of the volcano for more than 100 km. The maximum thickness of the deposit under these conditions would be 100 mm. If the eruption occurred during the month of May, the dispersion axis of the deposit would have an E-W course, and would extend for approximately 50 km on both sides of the volcano, with a maximum thickness of 300 mm for the deposit. In the event that the eruption occurs during the month of October, the ash would disperse towards the west for more than 200 km and with a maximum thickness of 100 mm for the deposit. The model that best fits what was observed during historical eruptions, is the one corresponding to scenario B for October.

Considering that in Costa Rica during the last decades there were important economic losses due to the fall of ash in the volcanoes Irazú (1963-65), Turrialba (2010-2018) and Poás (2017-2018), is necessary to include this type of threat in a hazard map, since eventually the map could be used as an input in a territorial planning with a preventive approach.

Taking into account the above, for effects of the hazard map, the ash fall affectation models corresponding to scenarios B have been considered (Figure 8). In this map thicknesses are considered for the deposit of between 3 and 300 mm.

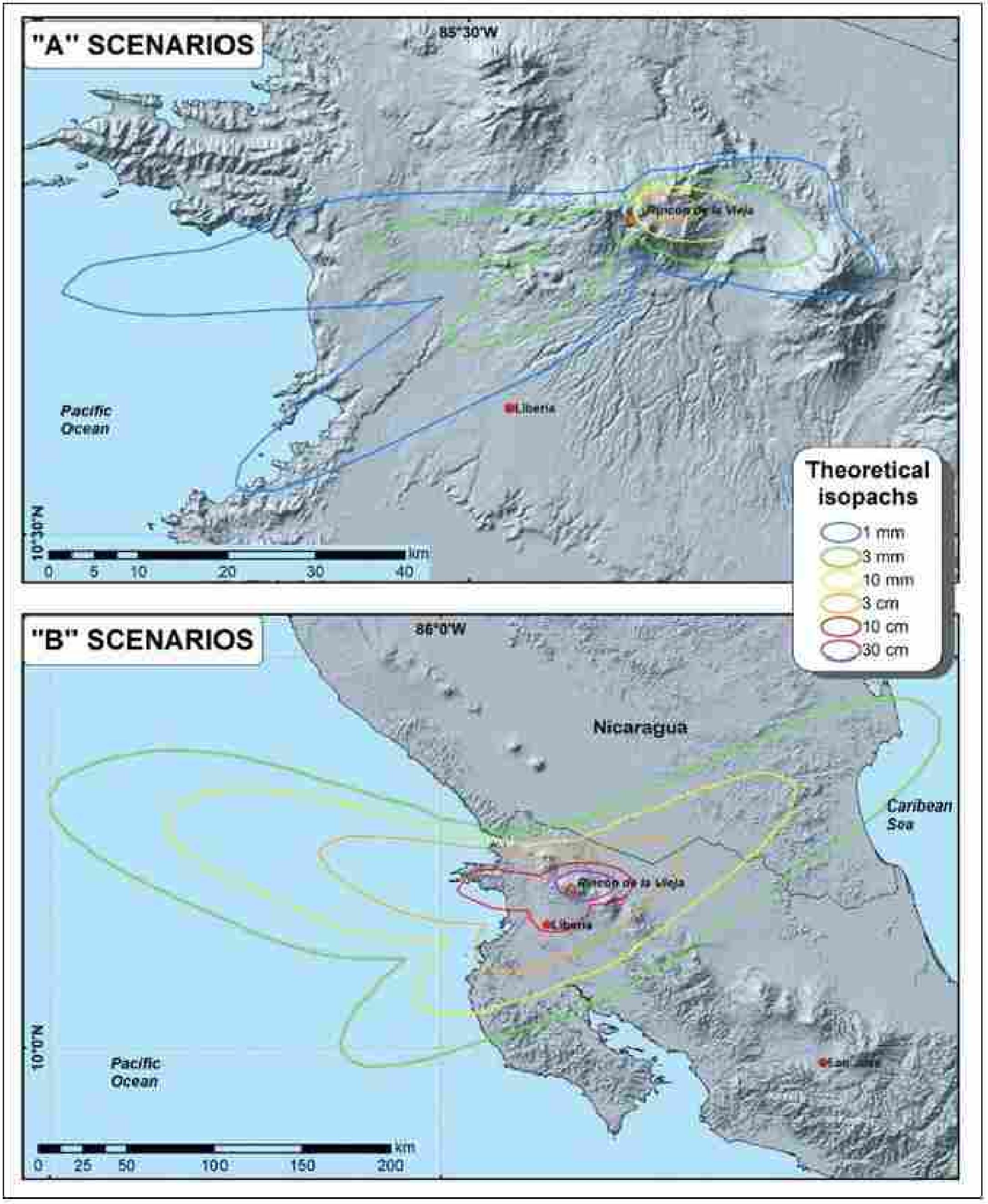

Figure 8 Ashfall models for A and B scenarios.

4.4 Gases and Acid Rain

The area that is currently affected by gases and acid rain is distributed mainly towards the west-southwest from the active crater, coinciding with the predominant direction of the winds. The area affected by gases and acid rain delimited in this work, covers at least 37 km^2 (Figure 9).

4.5 Lava Flows

The threat of lava flows has only been considered in the work of Soto *et al.* (2003b), and Soto & Martinez (2016). According to Soto *et al.* (2003b), the most recent lava flows, apparently had as source of emission the Von Seebach crater, reaching between 3 and 8.5 km away, and its age is higher than 3770 years. These authors delimit the zone of danger by

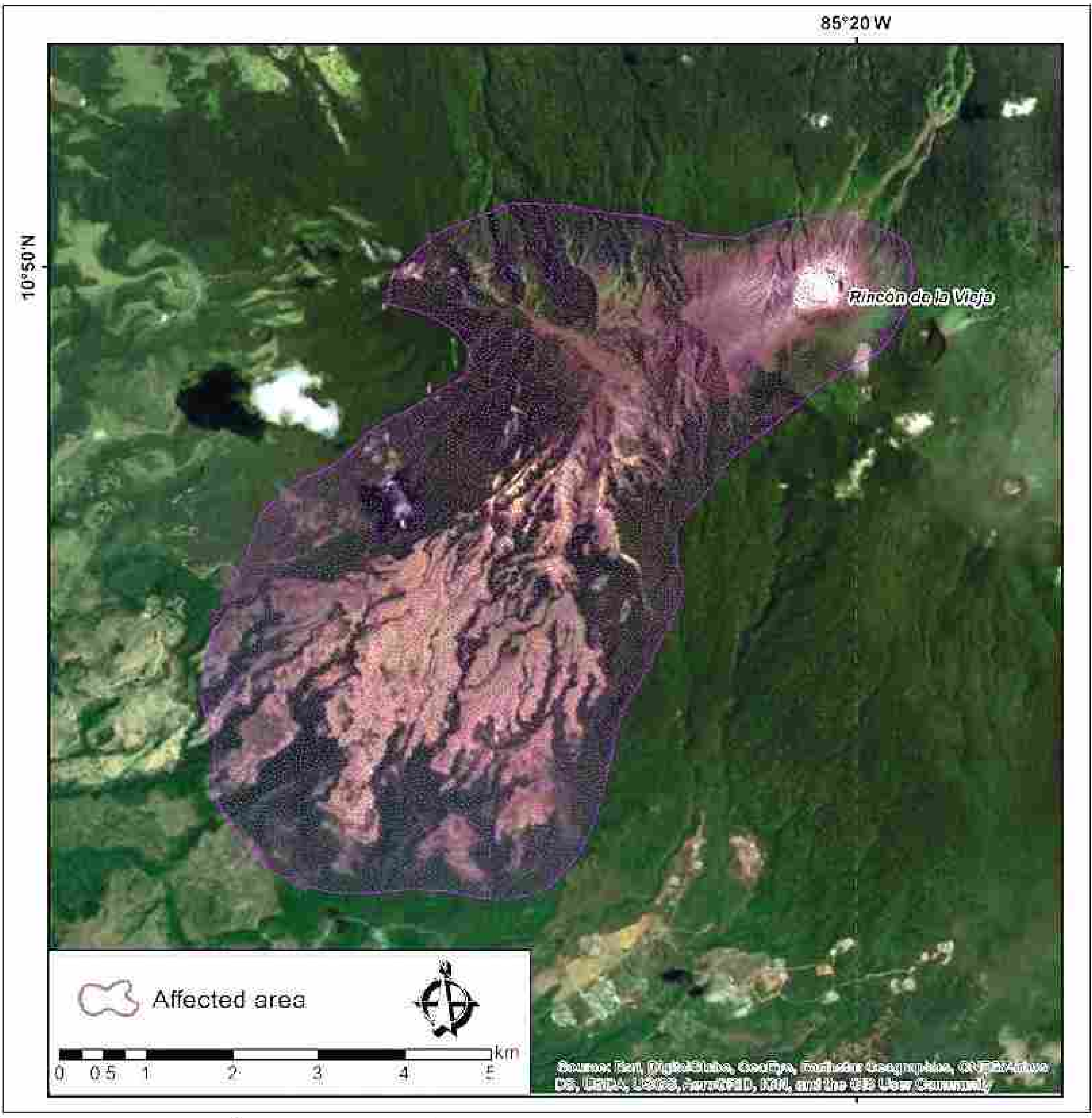

Figure 9 Area that is most affected by gases and acid rain.

luxuries of lava, within an area that covers up to 4 km to the north and 1.6 km to the south of the active crater, due to the topographic barriers that would prevent an eventual advance toward the south of new lava flows.

4.6 Ballistic

Soto *et al*. (2003b), mention that blocks of more than 1 m in diameter have been observed at distances of up to 1 km far from the active crater, while fragments of 5 cm have reached up to 8 km away. Historically, there is a record of bombs and blocks that have fallen down to 800 m from the rim of the crater.

In the particular case of this volcano, it is common for phreatic or phreatomagmatic eruptions to occur sporadically and suddenly, whose impact is restricted to the surroundings of the active crater. Faced with these eruptions, the communities closest to the volcano are not usually affected, but due to the hostile conditions of the topography in this sector, the visibility at the summit is often null due to the gases, and the almost total absence of places to shelter, the danger of suffering damages by blocks or bombs for those who are in the top or its surroundings is very high.

In existing volcanic hazard maps, zones of high and moderate danger have been delimited by ballistic projectiles in radii of 2 and 5 km around the active crater, respectively.

4.7 Flank Collapse

Kempter & Rowe (2000) developed a qualitative hazard map, in which zones of high and moderate danger were delimited in the case of lahars and avalanches. They determined that the greatest danger in the event of directed eruptions, or the collapse of an active crater sector, is for the northern sector.

Collapses of volcanic buildings are not very frequent events, but when they occur they tend to be highly destructive. Although the only historical case in Costa Rica was presented without consequences in the Irazú volcano on December 8, 1994, there are records of prehistoric volcanic landslides that have affected mainly the south-southwest slope of the Rincón de la Vieja volcano and some sectors of the top (Soto *et al*., 2003).

Although the possibility of collapse of a part of the volcanic building has not been thoroughly studied, authors such as Paniagua *et al*. (1996), Kempter & Rowe (2000) and Soto *et al*. (2003b) point out that, due to the geomorphological characteristics of the active crater and the constant eruptive and hydrothermal activity, its northern flank is apparently the most susceptible to collapse. An event of this type would possibly originate phenomena such as pyroclastic flows, avalanche debris and high volume lahars.

5 Results: Hazard Map

An integrated qualitative volcanic hazard map is proposed (Calder *et al*., 2015), since the final product is based on both the geological record, as well as deterministic modeling and pre-existing hazard information. (Figure11).

The final scale of the map is 1:50.000 for all the hazards, except the ashfall, since the latter is deployed on a scale of 1:800.000, due to the wide hypothetical distribution area of the ash. In Table 1 is presented a summary of the information displayed on the map, its source and the approximate scale in which it was generated.

In the presented map (Figure 11), information has been integrated on the volcanic hazards that could affect the study area in the short and medium term, as well as those that currently affect it.

The boundaries of the zone of proximal threat have been established through the generation of

Hazard	Source	Original scale
Gases and acid rain	Field data and analysis of satellite images	1:10.000
Lahars	Laharz models, field data and Kempter (1996) and Kempter & Rowe (2000) previous works.	1:10.000
Pyroclastic flows	Energy cone model (for H/L= 0.15 and 0.24)	1:10.000
Blocks and bombs fall	2 and 5 km radius	1:10.000
Ashfall	Ash3D models and field data	1:200.000

Table 1 Summary of volcanic hazards displayed in the preliminary map.

a deterministic model and have been validated by comparing them with the deposits of recent phreatic eruptions. This area is prone to be affected, even by eruptions whose eruptive columns do not exceed a few hundred meters above the rim of the crater.

Proximal hazard zone is not related to a specific type of threat, but is considered as very high hazard and its area was calculated considering a Heim coefficient of 0.24. It is an area of very high risk, both in small phreatic eruptions and during major events, because its position with respect to the active crater, and its topographic conditions allow this area to be more easily impacted by pyroclastic flows or surges, toxic gases in high concentrations, falling blocks/bombs, ash or hot mud. These same characteristics make it easier for lahars to be generated within their limits. On the other hand, the pronounced slopes that predominate in this sector, favor the occurrence of landslides with or without eruptive activity, whether triggered by gravity, seismic activity, deformation or saturation of the soil.

For the area that is susceptible to be affected by pyroclastic flows, the results obtained are consistent with the geological record information. The deposits of the most important pyroclastic flows that have been found for this volcano, date from the year 484, and are distributed towards the northern sector of the volcano, reaching the communities of Buenos Aires and Gavilán. These flows were extensively described by Kempter *et al.* (1996) and Soto *et al.* (2003b).

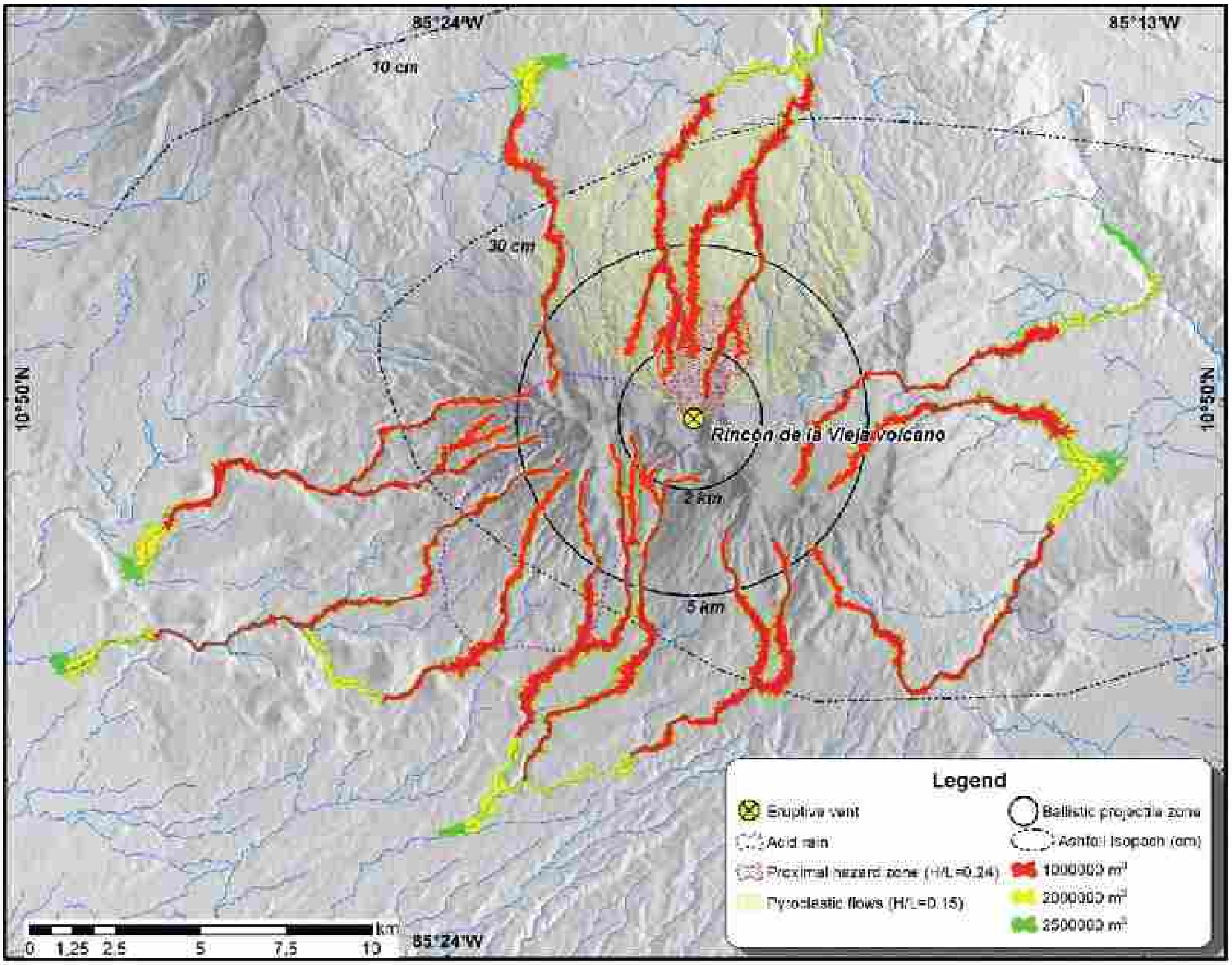

Figure 10 Volcanic hazard map of Rincón de la Vieja volcano

6 Conclussions and Remarks

During the last 3800 years the volcano had at least three periods of eruptive activity well marked: a subplinian eruption characterized by deposits of dacitic pumice; an eruption with generation of pyroclastic flows of scoria channeled towards the northern flank of the volcano that reached up to 10 km away from the eruptive focus; and the historical eruptive period, within which the eruptive activity was documented since the nineteenth century until today. This period is characterized by phreatomagmatic eruptions, being the most important of the period, the vulcanian eruption of 1967.

It has been observed that phreatomagmatic eruptions occur separated by intervals of four to five decades of relative calm, during which the predominant activity are phreatic eruptions and constant degasing, whose greater consequence for the environment comes from acid rain.

For those eruptions of which there is only geological record at the top of the volcano, and evidence of periods of phreatomagmatic or phreatic eruptive activity, it is advisable to carry out future studies, to enrich the existing events record and to better understand the eruptive histoy and dynamics of the volcano.

The hazard map generated in the present work is classified as an integrated qualitative type, the final product is based both on the geological record, as well as on deterministic modeling and preexisting hazard information of Kempter (1996), Kempter & Rowe (2000), Soto *et al.* (2003) and Soto & Martínez (2016).

The main volcanic hazards that threaten the northern sector of the volcanic building in the short term are lahars, pyroclastic flows, ash fall, affectation by gases and acid rain. The flows of lava and ballistic missiles would be restricted to a few kilometers from the source, and it is unlikely that they will reach the towns closest to the volcano, bearing in mind that the nearest houses are located five kilometers from the active crater.

In this document, both volcanic hazards that could affect the study area in the short and medium term are integrated, as well as those that affect the area at present.

It was not considered within the map, a possible collapse of the north wall of the active crater, because there are no conclusive studies that indicate that this may be a possibility in the short or medium term.

The area affected by gases and acid rain is concentrated around the active crater, extending to the southwest of the crater for about 8 km, depending on the prevailing direction of the wind.

As for the lahars, although these were modeled in the main channels that descend from the volcano, due to the geomorphological conditions of the summit as the presence of natural barriers, it is possible to affirm that the northern sector is the most prone to be affected by these flows. Although it should not be ruled out the possibility of occurrence of lahars in the other flanks into a scenario of plinian, subplinian, violent strombolian or even vulcanian eruption.

The ashfall with millimetric to centimetric thickness is a real danger for the whole sorroumding of the volcano along several kilometers; however, with adequate preparation its negative consequences can be minimized.

The areas delimited in the hazard map are based on the topographic and climatological characteristics at the moment when the map was performed, considering hypothetical eruptive scenarios, for which they do not establish definitive limits. These areas are rather guides, whose interpretation is limited by their respective scales. From these guides it is possible to detail in the field, if necessary for specific areas. For example, in the case that a site of interest is at or near the demarcated limit for a given hazard, the recommendation is to develop a localized hazard study to reduce uncertainty.

Regarding the description of the sedimentological and rheological characteristics of eventual lahars that affect the study area, these would vary according to their trigger mechanism.

If it is non-eruptive lahars, triggered by precipitation, these would drag materials that have been previously deposited in the upper river basins and would have dilute flow characteristics, mainly containing fine particles. They are the most common type of lahar in the area, and also the least destructive. Their deposits, when they are not eroded quickly, consist on centimetirc to decimetric layers of fine material, which can be confused with those of a normal flow of current. This normally happens in the channels of the Azul and Pénjamo rivers and their tributaries.

For lahars caused by phreatic, phreatomagmatic or magmatic eruptive activity, both water/debris proportion, as the fine fraction that allows to determine if the flow is cohesive or not, would be determined by the type of eruption, its duration, volume of material emitted and the amount of available water (rain or crater lake). However, in general terms, having constant eruptions as trigger mechanism, it can be expected that the lahars descend mainly by the Azul and Pénjamo rivers, and that have hyperconcentrated to debris flow characteristics, whose flood zones would be determined by the topography and the volume of the flow.

In the hypothetical case that a lahar is generated by the collapse of the crater wall, and considering the distance from the source, it is possible that the flow contains a significant fraction of angular materials of coarse granulometry, including metric blocks and vegetation, which would be immersed in a clay matrix, because it would be an explosive event with high fragmentation. This mixture would originate a flow that could vary from hyperconcentrate to debris flow, according to the proportion of water.

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